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## Antiprotons below 200 MeV in the interstellar medium: perspectives for observing exotic matter signatures

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Most cosmic ray antiprotons observed near the Earth are secondaries produced in collisions of energetic cosmic ray (CR) particles with interstellar gas. The spectrum of secondary antiprotons is expected to peak at  $\sim 2$  GeV and decrease sharply at lower energies. This leaves a low energy window in which to look for signatures of exotic processes such as evaporation of primordial black holes or dark matter annihilation. In the inner heliosphere, however, modulation of CRs by the solar wind makes analysis difficult. Detecting these antiprotons outside the heliosphere on an interstellar probe removes most of the complications of modulation. We present a new calculation of the expected secondary antiproton flux (the background) as well as a preliminary design of a light-weight, low-power instrument for the interstellar probe to make such measurements.

### 1. INTRODUCTION

The nature and properties of the dark matter that may constitute up to 70% of the mass of the Universe has puzzled scientists for decades, e.g. see [1]. It may be in the form of weakly interacting massive particles (WIMPs), cold baryonic matter, or primordial black holes (PBHs). It is widely believed that the dark matter may manifest itself through annihilation (WIMPs) or evaporation (PBHs) into well-known stable particles. The problem, however, arises from the fact that a weak signal should be discriminated from an enormous cosmic background, including a flux of all known nuclei, electrons, and  $\gamma$ -rays. Antiproton measurements in the interstellar space could provide an opportunity to detect a signature of such dark matter (see [2] and references therein).

High energy collisions of CR particles with interstellar gas are believed to be the mechanism producing the majority of CR antiprotons. Due to the kinematics of the process they are created with a nonzero momentum providing a low-energy “window” where exotic signals can be found. It is therefore important to know accurately the background flux of interstellar secondary antiprotons and to make such measurements outside the heliosphere to avoid any uncertainties due to solar modulation.

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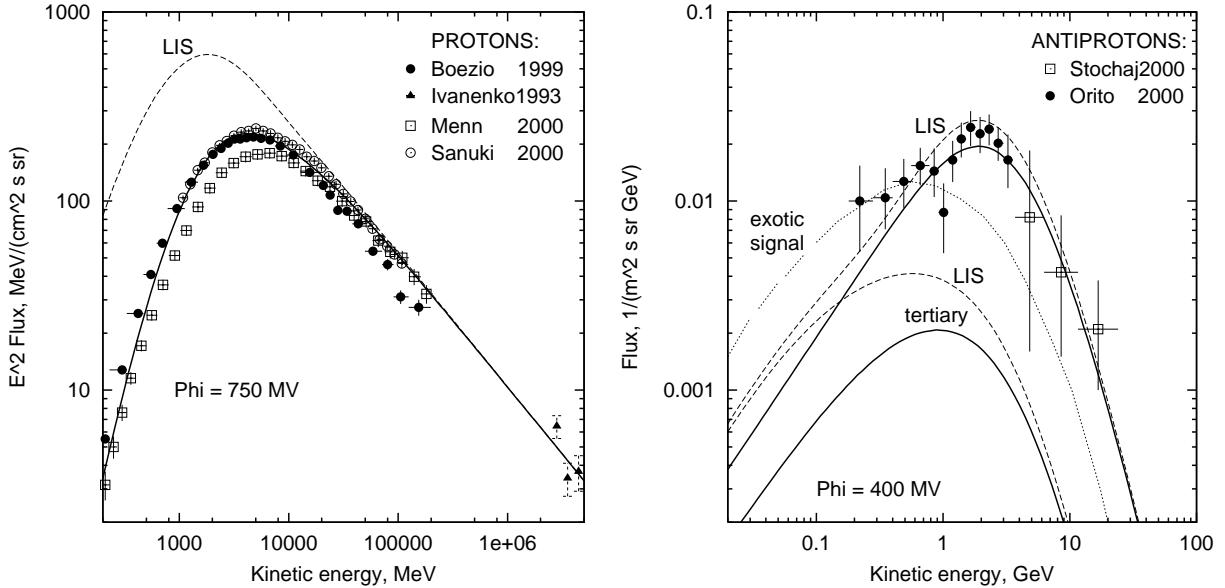


Figure 1. *Left:* Calculated proton interstellar spectrum (LIS) and modulated spectrum ( $\Phi = 750$  MV) with data [8–11]. *Right:* Calculated  $\bar{p}$  interstellar spectrum (LIS) and modulated spectrum ( $\Phi = 400$  MV) with data [12,13]. The top curves are the total background. The “tertiary” components (LIS and modulated) are shown separately. Also shown is an example exotic signal [14] extended to lower energies.

## 2. CALCULATIONS OF THE ANTIPROTON BACKGROUND

We made a new calculation of the CR  $\bar{p}$  flux in our model (GALPROP) which aims to reproduce observational data of many different kinds: direct measurements of nuclei,  $\bar{p}$ ’s,  $e^\pm$ ’s,  $\gamma$ -rays and synchrotron radiation [3–5]. The model was significantly improved, and entirely rewritten in C++. The improvements involve various optimizations relative to our older FORTRAN version, plus treatment of full reaction networks, an extensive cross-section database and associated fitting functions, and the optional extension to propagation on a full 3D grid. For this calculation, we used a cylindrically symmetrical geometry with parameters that have been tuned to reproduce observational data [5].

The propagation parameters including diffusive reacceleration have been fixed using boron/carbon and  $^{10}\text{Be}/^{9}\text{Be}$  ratios. The injection spectrum was chosen to reproduce local CR measurements,  $\sim \beta \rho^{-2.38}$ , where  $\beta$  is the particle speed, and  $\rho$  is the rigidity. The parameters used: the diffusion coefficient,  $D_{xx} = 4.6 \times 10^{28} \beta (\rho/3 \text{ GV})^{1/3} \text{ cm}^2 \text{ s}^{-1}$ , Alfvén speed,  $v_A = 24 \text{ km s}^{-1}$ , and the halo size,  $z_h = 4 \text{ kpc}$ .

We calculate  $\bar{p}$  production and propagation using the basic formalism described in [3]. To this we have added  $\bar{p}$  annihilation and treated inelastically scattered  $\bar{p}$ ’s as a separate “tertiary” component (see [6] for the cross sections). The  $\bar{p}$  production by nuclei with  $Z \geq 2$  is calculated in two ways: employing scaling factors [3], and using effective factors given by Simon et al. [7], who make use of the DTUNUC code, and which appears to be more accurate than simple scaling. (The use of Simon et al. factors is consistent since

their adopted proton spectrum resembles our spectrum above the  $\bar{p}$  production threshold.) The effect on the  $\bar{p}$  flux at low energies is however small, and the two approaches differ by about 15%.

We believe our calculation is the most accurate so far since we used a self-consistent propagation model and the most accurate production cross sections [7]. The results are shown in Figure 1. The upper curves are the local interstellar flux (LIS) and the lower are modulated using the force-field approximation. The two lowest curves in Figure 1 (right) show separately the contribution of “tertiary”  $\bar{p}$ ’s, which is the dominant component at low energies. The adopted nucleon injection spectrum, after propagation, matches the local one. There remains some excess of  $\bar{p}$ ’s. The excess for the lowest energy points is at the  $1\sigma$  level.

Many new and accurate data on CR nuclei, diffuse gamma rays, and Galactic structure have appeared in the last decade; this allows us to constrain propagation parameters so that the limiting factor now becomes the isotopic and particle production cross sections. At this point we cannot see how to increase the predicted intensity unless we adopt a harder nucleon spectrum at the source in contradiction with constraints from high energy  $\bar{p}$  data [3,5]. More details will be given in a subsequent paper.

### 3. ANTIPROTON DETECTOR

Very limited weight and power will be available for any experiment on board an interstellar probe [15]. We therefore propose a simple instrument which is designed to satisfy these strict constraints [2]. We base our design (Figure 2 left) on a cube of heavy scintillator (bismuth germanium oxide [BGO]), with mass of the order of 1.5 kg. The cube,  $42\text{ g cm}^{-2}$  thick, will stop antiprotons and protons of energy below 250 MeV. A time-of-flight (TOF) system is used to select low-energy particles. The particles with energy less than  $\sim 50$  MeV will not penetrate to the BGO crystal through the TOF counters, setting the low-energy limit.

The separation of antiprotons from protons is the most challenging aspect of the design. A low-energy proton (below 250 MeV) that would pass the TOF selections cannot deposit more than its total kinetic energy in the block. Therefore an event will be required to deposit  $> 300$  MeV to be considered an antiproton. A proton can deposit comparable energy in this amount of material only through hadronic interaction, which our Monte Carlo simulations show requires a proton with energy  $> 500$  MeV. The TOF system can effectively separate low-energy particles ( $< 250$  MeV) from such protons and heavier nuclei.

As a conservative estimate, we assume that all protons with energy  $> 500$  MeV have the potential to create a background of “ $\bar{p}$ -like” events and their integral flux in interstellar space is somewhat uncertain but would be  $\sim 1\text{ cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}$ . The exotic  $\bar{p}$  signal, to be significantly detected above the background, should be of the order of  $10^{-6}\text{ cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}$  in the energy interval 50–200 MeV, which corresponds to an expected signal/ $\bar{p}$ -background ratio of  $\sim 10$ . We thus can allow only one false antiproton in  $10^7$  protons.

Simulations to date indicate that the current design will have rejection power of  $\sim 2 \times 10^6$ . We expect to get the next factor of five by fine-tuning the design and selections. The efficiency of antiproton selection is shown in Figure 2 (right). The antiproton rate will be 0.1–1 particle per day, and the statistical accuracy will be  $\sim 10\%$  after 3 years of

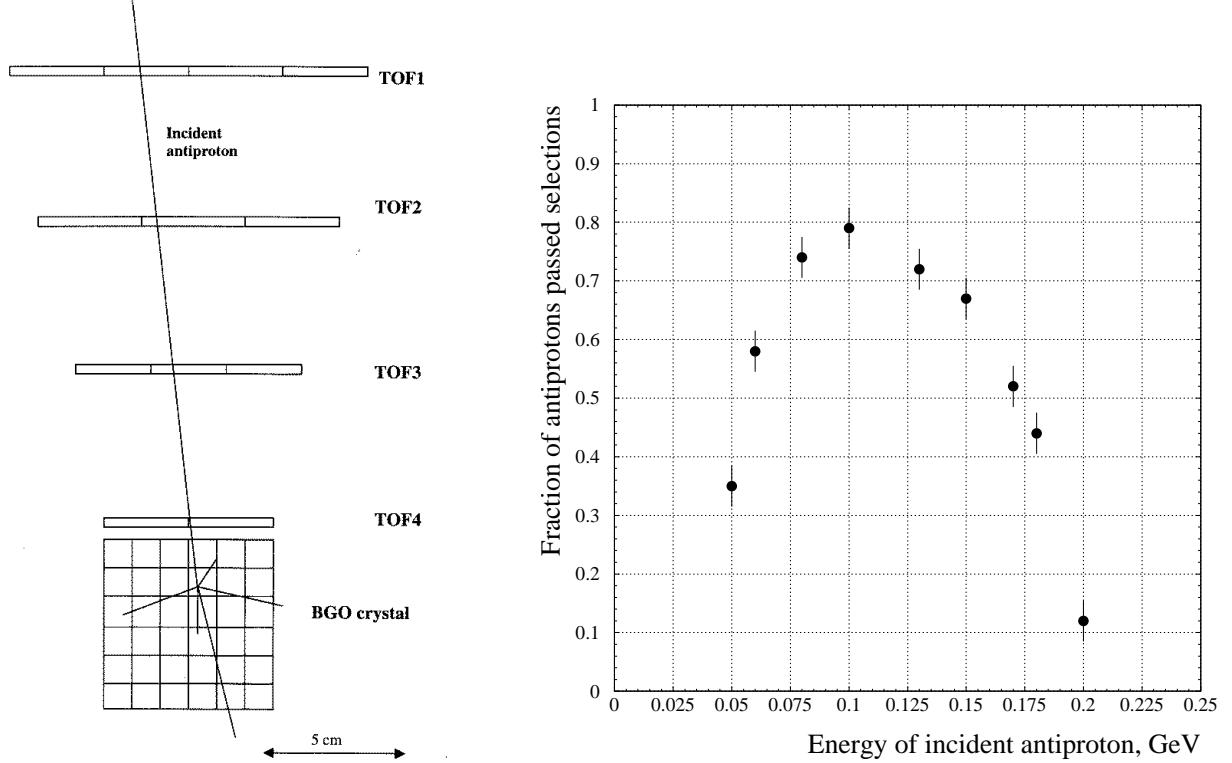


Figure 2. *Left:* Preliminary design of the detector. *Right:* efficiency for antiproton detection after selections applied.

observation.

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